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ENGINE MODIFICATIONS AND EXHAUST EMISSION CONTROL: A SURVEY AND APPRAISAL

W. E. Meyer

Robert A. Taft Sanitary Engineering Center
Cincinnati, Ohio

1962

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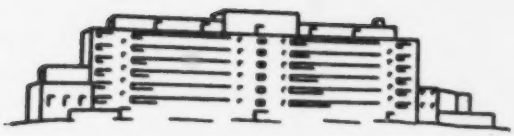
A Survey and Appraisal



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Engine Modifications and Exhaust Emission Control

A Survey and Appraisal

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for

U. S. Public Health Service

U. S. DEPARTMENT OF HEALTH, EDUCATION AND WELFARE
Public Health Service
Division of Air Pollution

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Cincinnati, Ohio

1962

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Engine Modifications and Exhaust Emission Control

A Survey and Appraisal

In this report the possibilities of solving the exhaust emission problem of motor vehicles by means other than afterburning devices are reviewed and evaluated as far as current knowledge and available information permits. These possibilities range from minor changes through major modifications of the conventional gasoline engine to diesel engines, new types of power plants, new transmissions, and other alternatives.

It is obvious that it would be a sounder solution to prevent the production of undesirable exhaust gas constituents than to eliminate them after they have been generated and emitted by the engine. An afterburner, whether it is of the catalytic or flame type, produces no direct benefits to the user. On the contrary, the afterburner increases the cost of operating the vehicle. Consequently, there is a strong incentive to search for solutions that would solve the emission problem by means that would at the same time improve vehicle performance, reduce fuel consumption, or in some other way benefit the user. Even if such measures increase the cost of the vehicle, the higher expense will be accepted much more readily by the public than it would be if the only return were an intangible contribution to the general welfare.

In examining possible measures and alternative solutions, it is therefore necessary to examine also the benefits or penalties that would accrue to owners and users. For instance, under the current California regulations the diesel engine qualifies without modification of any kind, provided it is so adjusted that it does not smoke. The question that must be answered is whether the diesel engine is or might become an acceptable power plant for the average passenger car. The report attempts to answer this question. In fact, one might say that the report examines the various possibilities for their potential of voluntary acceptance by the public.

The report passes definite judgment in only a few instances. In most cases not enough information is available to provide a factual basis for quantitative evaluation. Our ignorance about combustion and emissions is still considerable. We therefore have difficulty in predicting the effect of a particular modification when only 2 percent of unburned or partially burned fuel makes the emissions seriously objectionable.

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This survey cannot recommend a solution. Instead it indicates paths that may lead to acceptable solutions, and recommends studies that should provide some definite answers or that should lead to a better understanding of combustion in engines and hence to better control of it.

The author believes that the piston engine will remain the dominant power plant for motor vehicles for quite a number of years to come. Consequently, the larger part of the report deals with potential solutions to the emission problems that this engine type creates. Other power plants are discussed briefly.

GENERAL OBSERVATIONS

The American automobile engine of today is designed for good performance, smooth operation, and low cost. In the pursuit of these objectives, the air pollution problem created by exhaust emissions from ordinary gasoline engine has received very little attention until fairly recently. Since the gasoline engine is, on nearly all other counts, the most desirable power plant available, its design has become well standardized in all major aspects. Now that exhaust emissions have become a matter of concern, the tendency is to attempt to solve this problem by incorporating accessories that will remove from the exhaust gases the unwanted components, thereby avoiding major engines changes. In the long run it may be more desirable to modify the engine itself in such a manner that the exhaust products will be inoffensive to begin with, or at least much less offensive than they are now. This treatise will examine the possibilities for such an approach and assess their practicability and the possible objections of industry and users based on sacrifices that might be required in terms of performance, smoothness of operation, and cost.

Before such alternatives are reviewed and analyzed, it may be useful to inquire whether there are other solutions that do not involve altering the basic engine process and therefore do not change the basic composition of the exhaust gases, but either reduce their absolute quantity or permit the engine to be operated at regimes in which the proportion of undesirable exhaust constituents is at a minimum.

THE ENGINE-TRANSMISSION-VEHICLE SYSTEM

Engine Size

An automobile will generally perform better with the increased power that accompanies a larger engine. On the other hand, a

smaller engine tends to produce a smaller quantity of exhaust gases. It is difficult to predict very accurately the improvement obtainable from reduction in engine size, because a smaller engine would be operated differently than a large one in the same vehicle and the reduced performance would undoubtedly change driving habits and patterns. For comparison purposes, miles per gallon is a better criterion than either horsepower or piston displacement.

There is a marked trend toward smaller cars, as evidenced by the prominence gained by the "compact" cars in the past few years. Increased fuel costs may tend to accentuate this move. The American public likes high performance, however, and consequently the over-all horsepower-to-weight ratios have not changed significantly. Although mileage of the smaller vehicles is somewhat better than that of the larger cars, the gain is slight. Therefore, the emission picture has not changed significantly.

Probably much more important influences are exerted on the cumulative emissions by population changes in a given urban-suburban area, by the number of cars per family, by maintenance and replacement practices, and most importantly, by car usage and driving patterns. These factors cannot be discussed here, but they must be taken into consideration when the emission problem is projected into the future.

Transmissions

The automobile industry and the public will accept a reduction in the size of the engine or car if no serious sacrifice in performance is required. One theoretical possibility for maintaining performance standards while reducing engine size is the use of the infinitely variable transmission. Since such a transmission has high efficiency throughout its normal operating range, the engine can be run at much more economical combinations of load and speed than are possible now. For a given car, performance with such a transmission would be better than it is now. Thus present-day performance could be retained with smaller engines.

One such transmission system, the hydrostatic system is being seriously considered by industry today. While there seems little doubt that hydrostatic transmissions will find application in tractors and other special-purpose vehicles, it is much too early to say whether this system can be made practical for passenger cars.

Energy Storage

Another, though remote, possibility that would reduce fuel consumption is energy storage. When a vehicle is decelerated,

its kinetic energy is normally converted into heat, either by the friction of the engine or by that of the brakes. If this energy were stored and reused for accelerating the vehicle, a substantial saving in fuel should result, at least in city traffic. Some proposals for accomplishing this have been made.[1] It is also conceivable that the engine might be used to supply some energy to the storer, for instance while the vehicle is standing still. During this operation the system could permit the engine to operate at maximum efficiency. With proper control and adjustments, this should lead to a greater reduction in the total undesirable emissions than would result from the reduction in fuel alone.

Since with an energy storer, power is always and instantaneously available during a traffic stop for setting the vehicle in motion again, the engine could be shut down as soon as deceleration begins. The energy storer provides readily available and ample energy to restart the engine when it is needed again. It can be argued that, desirable as this may be from the standpoint of fuel consumption and exhaust emissions, it is impractical because power is needed for lights, radio, heater, air conditioner, battery charging, and other purposes while the vehicle stands still. It may be entirely practical, however, to operate these accessories from an auxiliary engine, and to provide heat and keep the main engine warm by letting the auxiliary drive a "water brake." The auxiliary can and must be adjusted and operated for minimum exhaust emissions. To use the "engine-off" feature with a storer that accumulates only enough energy for quick engine restarts is not attractive because the gains probably would not justify the complications of cost.

Such possibilities, farfetched as they may seem, deserve, in the opinion of the writer, to be studied and analyzed. If they lead to an appreciable reduction in the emission of dangerous exhaust products, the attendant complications may be worth while. The exhaust problem might be considerably alleviated, because engine operation would no longer be firmly tied to the vehicle performance. It should therefore be possible to avoid or at least substantially reduce those operating conditions during which the undesirable emissions are at a maximum.

THE CONVENTIONAL GASOLINE ENGINE

Full-Power Enrichment

Concerning engine performance per se, certain conditions deserve further discussion. There is first of all the full-power condition, at which the engine is operated rich. This enrichment is used for two reasons: (1) maximum power is developed when the mixture is slightly richer than stoichiometric (best economy

occurs at slightly leaner than stoichiometric), (2) excess fuel supresses detonation.

Full-throttle operation occurs most frequently with low horsepower-to-weight ratio vehicles (underpowered cars and trucks). For such vehicles a lean full-power setting is not attractive because it involves a sacrifice in performance. In vehicles with a high power reserve it makes little difference what the emissions are at wide open throttle because the throttle is opened fully only rarely. Various studies, for instance one by DuPont[2], show that the time spent by vehicles in urban and suburban traffic at wide-open throttle is minimal (a few seconds out of every hour).

Operation with rich mixtures at wide-open throttle results in heavy emission of carbon monoxide. On the other hand, nitrogen oxide emission increases as the stoichiometric mixture ratio is approached. It is therefore difficult to say whether leaning would bring about an over-all gain. Prediction is the more difficult because design for leaner operation will also involve other changes, such as ignition timing, compression ratio, fuel specifications, etc. All of these changes influence the production of nitrogen oxides, which in turn influences the knock susceptibility of the engine.[3]

Full-power enrichment for knock control can be eliminated by specifying for the engine a more knock-resistant fuel. Since such fuels are more expensive, the danger is always present that the user will readjust the engine for a lower octane fuel. Redesigning the engine for lower knock susceptibility would be a safer approach. A third possibility is to provide internal cooling by water injection, by the addition of an antiknock compound, or by the use of a two-fuel system in which the engine receives a highly knock-resistant fuel at full load only. These latter methods have been proposed in the past as means for solving the problems posed by high-compression engines, but they have not found acceptance because of the attendant cost and complication and because of the negligence of operators in replenishing the secondary fuel regularly.

If full-power enrichment must be employed and measures to control it are thought necessary, this approach might be considered: the throttle opening would normally be limited to some value below wide open; only when the vehicle speed was above a certain value could the throttle be opened fully. This would prevent rich operation in city traffic, but would still permit rapid passing maneuvers on the open highway. In addition, a device that senses grade could override the throttle-opening limit so that full power would be available for hill climbing. One argument against such devices (or similar ones designed to restrict other operating

modes) is that they would be tampered with. This is true; but if the restrictions they impose are reasonable, the vast majority of motorists will not attempt any "improved" adjustments.

The problem of full-power emissions must also be considered with unconventional engine processes. Some of these aim for full-power operation identical to that of conventional gasoline engines in order to retain the high specific output of the latter.

Lean Part-load Operation

A passenger car operating at constant-speed normal-load conditions consumes little power. For such light-load operation the carburetor produces a relatively lean mixture. Hence, gain in emission control in this area is questionable, since a significant gain would be necessary to accomplish any great over-all improvement.

It must be recognized that constant-speed cruise conditions contribute only a relatively small amount to the total emissions as obtained by the current 11-mode California driving cycle (combined weighting factor: 0.168). Consequently, unless improvement is appreciable, the net gain will be small.

It has been shown that leaning the mixture and retarding the spark can bring about significant reductions in hydrocarbon emissions under constant-speed constant-load conditions.[4,5] (In these regimes carbon monoxide and hydrocarbon content move together.) Probably still greater improvements might be obtained by concurrent refinements in the carburetor and manifold.

Whether these gains can be realized in practice remains to be seen. A car with a lean carburetor setting tends to surge when attempting to hold constant speed. And although lean settings give better mileage, spark retard negates this gain. Most importantly, lean settings bring the engine close to the condition at which ignition becomes uncertain and cycle-to-cycle variations increase. Thus any deterioration in carburetor adjustment or from other causes will produce a significant increase in hydrocarbon emission. In fact, an engine that originally was set lean may produce higher emissions than a corresponding one that was set richer.

More stringent carburetor calibration, better resistance of carburetor and ignition system to deterioration, better ignition systems, better control of engine deposits, and other measures may enable leaning, in combination with improvements at other than the cruising modes, to keep emissions below the maximum permitted by the California standard.

Idle, another steady-state condition, is subject to essentially

the same rules and limitations as the 20- to 50-mph road-load conditions (which are just "off idle" with high-powered cars). Leaning usually cannot be carried as far as at higher loads because of greater dilution of the fresh mixture by residuals and because ignition is more critical (conditions for ignition are less favorable and ignition system output is lower at lower speeds). Spark retarding is beneficial at idle, too.

In the California 11-mode driving cycle, idle has a weighting factor of only 0.042; thus improving it alone will not influence the composite hydrocarbon emission picture significantly. Carbon monoxide emission is almost entirely a function of fuel-air ratio and is insignificant as long as the mixture is leaner than stoichiometric. Since such mixtures are readily obtained at all steady-state conditions except idle, leaning the idle condition remains a challenge.

Acceleration Enrichment

With carburetor engines it is necessary to supply an extra amount of fuel when the throttle is opened. Acceleration enrichment is needed because the carburetor lags in going to the new condition and also because the intake manifold "runs wet", that is, there is a film of fuel on the manifold walls and this film is heavier for the larger throttle openings. Thus, when the throttle is opened, extra fuel is needed to make up for the deficiency in the fuel supply by the carburetor and to bring the film to the level required by the new condition. Since this extra fuel does not reach the cylinders, it does not affect the exhaust emissions, provided the accelerating pump is set so that the temporary enrichment just satisfies the requirements.

Correct setting of the accelerating pump is difficult to obtain and maintain. In practice the pumps are usually set too rich, since engines tolerate over-richness readily. Because acceleration enrichment requirements vary with temperature, fuel types, engine condition, etc., compromises are necessary as long as engineers and the public insist on unhesitating throttle responses. It is unlikely that acceleration enrichment can be controlled entirely by an automatic device that is both practical and satisfactory. The only way open is to so design the carburetor and manifold that minimum enrichment will be needed. Manifold heating by coolant or the exhaust gases is a step in that direction, since it reduces the fuel film on the manifold walls. But the wall temperatures are a function of the operating conditions that precede the accelerating process. For minimum enrichment this situation would have to be compensated for by an automatic device that corrects the acceleration fuel quantity for temperature.

Deceleration Emission Control

Hydrocarbon concentration in the exhaust is highest during closed-throttle deceleration. Originally it was thought that the remedy lay in cutting off all fuel flow whenever the throttle is closed completely while engine speed is above idle. This does eliminate the flow of fuel from the idle system into the engine, but unfortunately introduces several problems, among them poor engine response on reacceleration.

Furthermore, as the throttle is closed, the carburetor lags again and temporarily discharges more fuel than it should. In addition, the lowering of the pressure in the manifold causes the fluid film to dry up. Thus, during the initial part of the deceleration period the cylinders receive a large amount of excess fuel for which insufficient air is available.

Considerable effort by the automobile industry(6) has not produced a practical solution to the deceleration emission problem. A promising solution consists of a "vacuum limiter." This device opens the throttle whenever a certain vacuum (greater than idle vacuum) is reached, as it is when the vehicle drives the engine. A recent design and application are reported in a study by an automobile manufacturer.(5) Although a noticeable reduction of emission is obtained with the vacuum limiter, the open throttle reduces engine braking noticeably. It has been estimated that this may reduce the life of brake linings by as much as 20 percent.(7)

Another promising solution consists of providing maximum spark advance during closed-throttle deceleration.(7) This brings about an improvement because it provides more time for the very slow combustion of the heavily diluted mixture in the cylinder. A special device is needed to apply full manifold vacuum to the distributor, since the connection between carburetor and distributor is normally interrupted when the throttle is closed. The additional power developed by the better combustion reduces vehicle deceleration somewhat, but so slightly that the average driver would not be aware of the change.

The initial emission peak might be dealt with by temporarily admitting some air to the intake manifold direct from the atmosphere to lean out the excessively rich mixture existing at that time. This air admission might be controlled by a viscous damper (similar to the accelerating pump) to take into account the amount of the throttle travel and the rapidity of throttle closing.

Valve Overlap

Some engines employ rather large valve overlap; that is, the

exhaust closes an appreciable number of degrees after the intake valve has opened. At high speeds this promotes better "breathing" because the cylinders are scavenged better and therefore aspirate a greater amount of fresh mixture, and consequently power output is greater. At low speeds and light load, including idle, high valve overlap produces poorer scavenging: the exhaust valve is still open during the beginning of the intake stroke, inflow of fresh mixture is reduced by the high manifold vacuum, and combustion products are sucked back into the cylinder. Under these conditions a richer mixture must be used than would otherwise be necessary to insure proper running of the engine.

The richer mixture tends to increase the emission of both hydrocarbons and carbon monoxide. Because the dilution of the fresh mixture by residuals may cause very poor burning, it is not possible to correct the condition by leaning.(5)

The problem is lessened by reduced overlap. How little overlap can be used depends on many engine design factors and in part on transmission design, because overlap has a decided influence on the shape of the full-load torque curve of the engine.

Rich Carburetor Setting

Much of the exhaust emission problem is created by the demand for smooth, responsive engine operation. This demand can be satisfied most easily by a rich carburetor setting. It is next to impossible to design and adjust a carburetor so that it combines optimum engine performance and "feel" with minimum fuel-air ratio under all conditions. The remedy is to set the carburetor richer than necessary throughout or at least over a good part of its operating range in order to cover up the lean spots. Although reasonable enrichment does not necessarily produce excessive exhaust emissions, this "necessary" enrichment makes it more difficult to comply with the emission standards.

Whether refinements in carburetor design can eliminate the necessity for "smoothing by enriching" is a matter of conjecture. Some of the devices and provisions discussed earlier would have to be included in any major redesign to assure maximum benefit from such an undertaking.

Cycle-To-Cycle Variations

Lately the problem of variations from cycle to cycle has received attention.(8) It has been reasoned that if all cycles were identical with the best ones, considerable gains in economy and output could be achieved. The major factor that has been found to

control the variations is the fuel-air ratio in the cylinders. The cyclic variations are at a minimum when the mixture is slightly richer than stoichiometric. Increase in compression ratio has a steadying effect because scavenging is improved. Dilution with residuals is detrimental.

These findings are not at variance with the effects of the same variables on exhaust emissions. The basic cause for the increase in cyclic variations and exhaust emissions as the lean limit is approached is uncertain ignition and slow inflammation. Perhaps the only practical means for lowering the lean limit of a homogeneous-charge engine is to employ several simultaneous sparks. How effective this would be with regard to emissions is unknown.

Engine Deterioration

If a carburetor goes leaner in service, this is noticed immediately because the engine becomes rough, response is poorer, and actual missing occurs. If gradual enrichment develops, however, it goes unnoticed for a long time because nothing occurs that is easily detected. Unless the owner very carefully records fuel consumption, the amount of enrichment can become quite large before it reveals itself in engine performance and behavior. Although present-day carburetors are marvellously efficient, they go out of adjustment relatively easily. Manufacturers therefore tend to adjust the carburetor on the rich side because the tolerance is so slim on the lean side of the best setting. It should also be noted that, because of the close relationship between the required mixture strength and spark energy, the carburetor must be calibrated to provide for some deterioration of the ignition system.

The engine can deteriorate in other ways to produce an adverse effect with respect to exhaust emissions. For instance, as deposits build up in the combustion chamber, greater amounts of emissions are produced.(4,5) Leaking exhaust valves could admit unburnt mixture to the exhaust system, greater oil consumption could increase the unburnt hydrocarbons in the exhaust, spark plug deterioration could do the same, and there may be still other factors. These points have not yet been studied in detail.

THE MODIFIED GASOLINE ENGINE

So far only minor modifications of the standard gasoline engine have been discussed. These involve, aside from adjustments, closer tolerances and other minor changes or accessories and do not require redesign, either of the engine or of its major compo-

nents. We shall now examine the question of what gains might be obtained from more radical departures from current design practices.

Combustion Chamber Changes

It has been shown rather conclusively that the major source of hydrocarbons in the exhaust is the quenching of the flame at the combustion chamber walls.(9) This means that chambers with a low surface-to-volume ratio should be superior to chambers with a high ratio. Therefore, compact combustion chambers should be examined for their emission characteristics.

The thickness of the quench zone is undoubtedly reduced if pressure and temperature are increased. This can be accomplished by raising the compression ratio or by increasing the wall temperatures. Since both measures increase the tendencies for knock and pre-ignition, it would be necessary to employ them with discretion.

Dilution by inert gases increases the thickness of the quench zone. Thus good scavenging would seem to be beneficial. Valve overlap and tuning of the intake and exhaust systems affect scavenging, but, since this is due to the dynamics of gas columns, improvement at one condition may be negated by poorer scavenging at another. On the other hand, apparently a significant portion of the unburnt hydrocarbons remains in the residuals.(9) If this is so, improved scavenging would expel them into the exhaust system, and thereby prevent their being consumed during the next cycle.

Turbulence tends to reduce the thickness of the squench zone. Thus it should promote more complete combustion. On the other hand it increases heat transfer, and thereby reduces temperatures and pressures. Yet turbulence also tends to homogenize the mixture throughout the chamber, and this should be beneficial.

Much depends on how the turbulence is produced and how it affects various parts of the chamber. If the turbulence is produced by squish (compression turbulence), zones of very high surface-to-volume ratio are created and these may obscure any benefit derived from the turbulence itself. Again much must be learned in this area before it is clear what measures will improve the quality of exhausts.

This discussion of combustion configurations had reference to hydrocarbon emissions only. In an appraisal of the gains that might be attainable by the various possible modifications,

consideration must also be given to the production of oxides of nitrogen, which are produced in greater quantities as the temperatures increase. Therefore any research on combustion chamber modifications should include monitoring of the nitrogen oxides production.

Alternative Ignition Systems

Although there are many ways in which engine deterioration or malfunction might affect the exhaust emissions, this is a largely unexplored area. The ignition system is commonly considered the most unreliable component of an engine, and presumably any improvement in ignition system reliability should have a salutary effect on the total emissions from motor vehicles. The question is whether unconventional ignition systems could bring about a significant improvement. At the moment, relief from this quarter is not likely. Higher-energy sparks will insure proper ignition of somewhat leaner mixtures and so will less massive electrodes (because of reduced quenching effects), but the possible improvement by these and other similar steps is of minor magnitude. It is an open question whether "better" ignition of the mixture alone can bring about a significant change in the amount of exhaust emissions.

It has been mentioned that multiple spark sources are one means for reducing cycle-to-cycle variations. It may therefore be advisable to determine whether a dual ignition system would reduce emissions. Since dual ignition (two spark plugs firing simultaneously) also gives a measure of knock control, more freedom in combustion chamber design is gained and thereby additional improvement becomes possible.

Mixture Preparation Problems

In the past, the only gains offerred by substitution of alternative fuel systems for the standard carburetor were slightly better power, a sometimes doubtful improvement in fuel economy, and better response or "feel." Except under unusual circumstances, the higher cost of such systems was an effective deterrent to their adoption. Considerable extra cost could be absorbed, however, if in addition exhaust emissions could be reduced sufficiently to eliminate the need for an afterburner. This solution is attractive, since only would the emission problem be solved, but also the customer would receive tangible benefits in performance and operating economy.

The introduction of alternative fuel systems has been hampered in the past not only by cost but also by the desire to use

any new system as a direct replacement for the carburetor without other major engine changes, such as in manifold and port design, valve timing, etc. The latter restriction has made many fuel systems appear less attractive than they might have otherwise. Similarly, it is not likely that a new fuel system will solve the emission problem unless advantage is taken of all additional means for improvement.

It is imperative, then, that any new fuel system is treated as an integral part of the engine. This has been done only when the objective has been maximum engine output. Consequently, the true potential of alternatives to the carburetor is not known. Furthermore, data on the effects of such alternatives on exhaust emissions are very limited. Therefore, much of the discussion that follows is of necessity based on speculation.

Improvement over the carburetor is possible via two avenues: better mixture preparation and better fuel metering. Since the standard spark-ignition gasoline engine involves the combustion of a homogeneous fuel-air mixture, it is of interest to know what might be gained by perfect mixture preparation. Here again, little information is available, but Huber shows that when the fuel is supplied as vapor the engine will operate satisfactorily down to much leaner air-fuel ratios than can be attained with a carburetor.(10) Vapor-feeding has the advantage of better part-load economy and thereby reduces the amount of fuel consumed. It is an open question, however, whether the undesirable exhaust emissions are reduced in proportion to the lesser amount of fuel consumed. Huber does show that the carbon monoxide content of the exhaust gases at a given air-fuel ratio is approximately independent of the quality of mixture formation. Other exhaust constituents may increase or decrease, depending on the interaction of the several factors that influence their production. The conjecture that emission of unburnt hydrocarbons is reduced would seem to be valid, however.

It is difficult to visualize how a perfectly homogeneous mixture could be supplied to an engine in practice. The closest approach to this ideal is offered by pressure feeding systems.

Pressure Fuel Systems

There are four possible types of systems under this category: (1) continuous pressure feed to a single point in the manifold, (2) continuous pressure feed to individual points just ahead of the inlet valves, (3) intermittent feed near each inlet valve (usually fuel is discharged only while the valve is open), and (4) intermittent feed into the cylinders (discharge only during the intake stroke, since sufficient time must be available for the

formation of a reasonably homogeneous mixture). It is obvious that the problem of homogenizing the mixture becomes the more difficult the closer the fuel admission point is moved toward the cylinder and, in the case of intermittent injection, the later in the cycle the fuel is mixed with the air. (It is possible to make a virtue out of these shortcomings by deliberately aiming for stratification of the charge; this alternative will be reserved for the discussion of new engine processes.) No information is available on the influence of these variables on exhaust composition. It stands to reason, though, that the gains, if any, will be smaller than those obtainable with vapor feeding.

Other factors may play a part. If the fuel is supplied next to or directly to the cylinder, the fuel or most of it will evaporate within the cylinder. This will reduce the mixture temperature. Unless this advantage is absorbed by a compression-ratio increase, it may have a beneficial influence on the production of nitrogen oxides. On the other hand, emission of unburnt hydrocarbons may increase, particularly if fuel is permitted to impinge on cold surfaces.

Admission of the fuel close to the cylinder will reduce manifold wetting. This may constitute a major advantage because it eliminates the need for acceleration enrichment and therefore cuts down or eliminates the peak that occurs in the initial part of the deceleration process.

When valve overlap is great and a premixed charge is used, some fuel may pass directly from the intake into the exhaust. Intermittent injection can prevent this if injection begins only after all danger of shortcircuiting has passed. There are additional fuel-system factors that may or may not affect exhaust emissions, but their influence is probably small. In the absence of systematic research it is impossible to assess them individually.

One other important factor represents a potential advantage of many pressure feed systems: the mixture ratio that the individual cylinders receive is more uniform. To what degree this advantage is realized depends on the individual fuel system. It depends also on the engine's air system because, unless the air is distributed uniformly, any advantage the fuel system may offer will be masked. Uniform distribution means not only uniform amounts of fuel in all cylinders but also uniform fuel composition.[11] When partial evaporation takes place in the carburetor manifold, some cylinders receive a greater share of some fuel fractions or additives than of others. Uniform distribution permits higher output and better economy and may have significant influence on exhaust emissions. It should be noted that some modern carburetor engines, at least over a limited range of conditions and while in optimum adjustment, have good distribution characteristics.

A pitfall that is peculiar to some intermittent-injection systems is cycle-to-cycle variation of the injections to the same cylinder. Obviously, such variations would cause difficulties. These can be overcome by setting the mixture control sufficiently rich, but this would be at variance with the endeavor to operate at the leanest possible fuel-air ratios. This is no indictment of intermittent injection in general, because some systems have negligible cycle-to-cycle variation.

Mixture Control Systems

In contrast to the standard carburetor, the feeding and the metering functions are completely separated in all of the fuel systems under discussion here. Thus no compromise between the two functions is necessary, and indeed, possibly the greatest advantage of alternative fuel systems is the potential of improved mixture control. The exact fuel flow demanded by economy, power, or emission considerations can be programmed into the control system (feedback systems do not seem to be practical), and necessary corrections for off-design conditions may be provided. The latter conditions include ambient pressure and temperature, engine and fuel temperatures, etc. If necessary and practical, a correction can even be made for fuel composition (via a density-sensing device). Thus, if such fuel systems are basically capable of improving the exhaust emission situation, control system design can assure that this improvement is realized in operation.

Another important point is that separate mixture control systems, if properly designed, will "hold calibration" much better than a carburetor does. Since pressure-feeding systems are also much less subject to wear and deterioration than carburetors are, performance should be much more stable. Of course, where crankcase blowby is fed back into the intake manifold, provision must be made so that variable blowby will not upset the metering program.[12] There is no "carburetor vent" problem,[13] since the only free fuel surface occurs in the tank of the vehicle and consequently there is no danger of enrichment from fuel vapors vented into the intake manifold.

Acceleration and Deceleration with Pressure Fuel Systems

It has been pointed out that with pressure fuel systems manifold wetting is considerably less than with ordinary carburetors, and may be completely absent. Thus the required acceleration enrichment due to this cause is very small. (It appears that even with a completely dry manifold some slight enrichment is desireable for optimum engine response to a step input.) Any control

system, if it is not electronic, will have a measurable response lag. Some systems permit this lag to provide automatically the needed acceleration enrichment.(14) In others systems in which lag tends toward lean during acceleration, design emphasis is placed on assuring extremely rapid response. What little enrichment may then still be needed is provided by slightly rich calibration of the system. In the absence of any studies of this problem, it cannot be stated whether these slight amounts of enrichment have a measurable effect on exhaust emissions.

With certain pressure fuel systems, another problem arises. In a carburetor, when the throttle valve is closed, some air flows through the idle system. This flow is independent of engine speed because the idle system behaves as a critical orifice and, since the fuel flow is proportional to the airflow, the mixture ratio remains essentially constant throughout a deceleration cycle.

With pressure fuel systems that have mixture control by manifold vacuum, the air flow is also essentially independent of engine speed. This means that air per stroke decreases with increasing speed. The manifold vacuum increases with speed, and this produces also a reduction in the fuel delivery per stroke. Fuel flow is not related to air flow under these conditions. The fuel reduction with speed is much smaller than the air reduction and therefore the mixture will be much too rich at high closed-throttle speeds. This excess fuel is wasted(15) and very probably increases the exhaust emissions.

To eliminate this fuel waste, various types of deceleration cutouts may be employed.(15) All these devices work on the principle of reducing fuel delivery above idle vacuum more rapidly with increasing manifold vacuum than in the power range. Thus zero fuel delivery is insured at the higher deceleration vacuums. From an emission standpoint this appears ideal at first sight. Unfortunately, at deceleration from moderate speeds, the manifold vacuum brings the fuel delivery just into the range between idle and zero. Emissions will be quite high under these conditions because the mixture will be too lean if it has been adjusted for minimum emissions at idle.

The desirability of making this transition range as narrow as possible suggests itself. The narrower range, however, would be felt by the driver as a step change in engine output and that would not only be a nuisance but also might seriously hinder maintaining constant speed in slowly moving traffic. Some compromise may be the answer to this problem.

Exhaust Retarding

It has been proposed to solve the problem of emissions

during deceleration periods by closing off the exhaust line whenever the engine is driven by the vehicle. Valves are in use on diesels as a means for increasing engine drag during downgrade operation of the vehicle. With such "exhaust retarding," the engine operates like an air compressor pumping into a closed vessel. Theoretically the engine consumes no air under these conditions but in practice there is some airflow because of blowby and leakage.

In a gasoline engine, a second valve must be provided to connect the intake manifold to the atmosphere. This valve is necessary not only for preventing fuel from being aspirated with the makeup air but also for admitting the air needed to build up pressure in the exhaust system. (The retarding condition can be reached only via the closed-throttle condition.)

Whether any benefit with regard to emissions is obtained by blocking the exhaust has not been demonstrated. Obviously there will not be any emission as long as the exhaust is closed off. But what happens to the fuel film on the intake system wall, which under normal conditions produces the emission peak at the beginning of the deceleration period? Could exhaust retarding be engineered to make it acceptable to the average driver? These and other questions have at the moment no known answers.

There is little doubt that exhaust retarding is of benefit in down-grade operation since it relieves the load on the vehicle brakes. It also keeps engine temperatures up. In city traffic it may increase fuel consumption because it provides more rapid deceleration than does merely closing the intake throttle. Since no vacuum is generated in the cylinders during retarding with blocked exhaust, no oil is sucked into the combustion chamber. The emission picture may benefit from this, not only directly but perhaps also indirectly, because spark-plug fouling is reduced. On the other hand, the blowby rate is increased, but it is not known whether this increases the crankcase emissions. The blowby consists only of air, lube oil vapor, and possibly lube oil products.

Because blowby (and leakage past the exhaust valve stems) may have a bearing on the practicability of exhaust blocking as a means for reducing emissions, any promising results that may be obtained should be checked on worn engines before the findings are accepted as conclusive.

Concluding Remarks Concerning Gasoline Engines

In summary, it may be said that there are various possibilities for reducing the exhaust emissions from conventional

gasoline engines without deviating from the current engine process. No single possibility offers a complete solution, however. Whether it is possible to combine various modifications in such a fashion that the end product is acceptable from the standpoint of atmospheric pollution is difficult to say. We do not know well enough as yet what effects every one of the numerous possible modifications would produce. Separate studies of individual factors may have limited value because of the numerous interrelationships and the new problems created by operation of the vehicle in traffic after certain modifications have been made. The writer believes that only an integrated program to develop a "clean" engine for a specific vehicle and service can provide this answer. He is not prepared to say whether such an undertaking would be worthwhile. Much depends on whether emissions other than unburnt hydrocarbons, as now defined in the California regulations, and carbon monoxide must be considered. Possibly the principal consideration should be whether other engine processes offer greater promise of success.

DIESEL ENGINES

So far we have discussed gasoline engines of premixed-charge and direct injection types, with spark ignition and load control by throttling. The next question that must be asked is whether there are other existing engine types that offer a solution to the exhaust emission problem. Under current California regulations, the diesel engine qualifies immediately without afterburner or similar device. Under all conditions its emissions of unburnt hydrocarbons and carbon monoxide are well below the mandatory limits. This fact may well lead to its introduction into vehicles other than heavy trucks and buses, in which it is the almost universal power plant. Because diesels, particularly in stop-and-go service, show much lower fuel consumption than gasoline engines, they are now beginning to show up in smaller trucks and taxis, even in areas in which there is no immediate threat of exhaust emission regulation. Their general use in passenger cars, however, is not very likely.

Passenger Car Diesels

Even if diesel passenger cars should come into use in larger number, the honeymoon of lower fuels cost would not last very long. There is actually a world glut of the lighter crude fractions, so that any substantial increase in the use of the heavier fractions would alter the fuel price picture sufficiently to wipe out even most of the cost advantage due to the lower specific fuel consumption of the diesel. Diesel fuel would also have to carry its full share of the distribution cost (filling stations, etc.), which

it does not do now. Finally, it must be considered that the Federal Government and all States of the Union today depend heavily on the revenue from road fuel taxes. If these revenues should fall because vehicles use less fuel, it is almost certain that the tax rates on fuels that permit lower consumption would be raised to make up for the revenue loss.

Engine Weight

Would the diesel then still have a chance as a passenger-car power plant? Probably not. First of all, its weight per horsepower is higher. The reasons are that all existing diesels are designed for heavy-duty service and, more fundamentally, that the diesel must be designed for higher working pressures. This is done for four reasons. (1) Diesel compression ratios are much higher than those of even high-compression gasoline engines --20:1 versus 10:1. (The 20:1 figure is used here because passenger-car engines would have to use such ratios even though large truck engines range from only 14:1 to 17:1.) (2) The combustion pressures are higher. (3) The usable maximum fuel-air ratios of diesels are lower than those of gasoline engines, and therefore a larger engine is needed for producing the same mean effective pressure. (4) Because of the heavier moving parts and the difficulty of getting good combustion at high engine speeds, diesels have lower top speeds than gasoline engines. Thus, a diesel of equal power is heavier than its gasoline counterpart; the lighter the vehicle, the greater is this weight disadvantage. The use of two-cycle engines and supercharging can alleviate this handicap to some extent, but not sufficiently to invalidate these general conclusions.

Engine Cost

A heavier engine is also more costly, but it can be assumed that the cost of diesel engines would come down appreciably if diesels were produced in the same quantities as gasoline engines. In comparison with the latter, diesels are still penalized by the expensive fuel system they require. Currently, the injection systems of small engines may cost as much as the rest of the engine. Some breakthrough in design and larger quantities may change the diesel's relative price position, though, since almost any major modification of the gasoline engine in the direction of lesser exhaust emissions will make it more expensive. The gap in first cost would also be narrowed if gasoline engines were equipped with the afterburners of other accessories that would be required to meet certain emission standards.

Diesel Future

There remain other disadvantages of the diesel that militate against its use in passenger cars: difficult cold starting, obnoxious exhuast odor (even if smoke is fully suppressed), low-volatility fuel that smells and stains clothes permanently, etc. Some of the existing problems will no doubt be solved or least alleviated as time goes on, but currently nothing is visible that promises to change the situation appreciably.

Diesel Exhaust Emissions

Although it has been reasoned that the diesel is not likely to see widespread use in passenger cars, there are a considerable number of diesel-powered utility vehicles in use today and their number is likely to increase. Therefore diesel emissions cannot be ignored altogether.

Current concern centers mostly on the full-load behavior of diesels. For instance, the smoke problem becomes serious only at full load. Unpublished studies have shown, however, that even trucks operate at wide-open throttle only rarely in urban traffic. Hence, since carbon monoxide production is closely tied to smoke density and since the emission of hydrocarbons is low, diesels present no serious problem in this respect. Smoke can be policed relatively easily, and restrictions concerning it do not have any objectionable side effects. In general manufacturers rate their engines at the smoke limit in the interest of fuel economy and engine cleanliness.

There are other problems. Nitrogen oxide emissions can be higher with diesels than with gasoline engines in the middle-load range. Diesel exhaust causes odor and eye irritation. The exhaust also contains 3,4 benzpyrene, which is suspected of being a contributor to the high incidence of lung cancer. Information on the production of these offensive byproducts is still incomplete because their proportions depend on the particular engine type (combustion chambers), fuels (diesels accept a fairly wide variety of fuels), maintenance, operating conditions, and other factors. More information is needed before conclusive judgment can be passed.

It is generally assumed that if the diesel is a problem from the air pollution standpoint, it is significantly so only at full load. The possibility should not be ignored that at part load certain types of emissions may reach levels that, at least in some localities deserve to cause concern. Virtually no research has been done in this area. What makes the situation complex is that there are many different types of diesel combustion systems that can

conceivably behave quite differently from each other at light loads. For instance, certain engines are known for their excessive smoke and odor during idle.

The situation is further complicated by the already mentioned fact that diesel fuels are much less uniform than gasolines. While competitive forces tend to make gasolines "better" and more uniform, the opposite seems to be true for diesel fuels. Since the main attraction of the diesel engine is the saving in fuel cost, there is an overriding and powerful incentive to provide (and to use) the cheapest fuel possible. This calls for a minimum of refining and treating, no additives, etc. The result is that fuels differ widely. Engine builders are constantly at work to broaden the range of fuels that an engine can use. Consequently, the emissions are likely to vary widely, depending on the type and brand of fuel being used.

Sparked by developments sponsored by the Army, commercial interest is gradually developing in the so-called multifuel engines. These are essentially diesels that can utilize a broader range of fuels, hopefully including motor gasoline. As the prices of diesel fuel and gasoline approach each other, such engines make more and more economic sense. Thus all studies on diesel engines should be extended to include the entire range of fuels that the engine under test will tolerate. It should be recognized that the poorest diesel fuel an engine can use is that with which light-load operation and idle are just possible. Under these conditions combustion is marginal, and it is very likely that such marginal operation may be accompanied by high emission rates.

The current trend toward smaller diesels leads in the same direction. Smaller cylinders have higher surface-to-volume ratios and therefore higher heat losses. Since, in the diesel, ignition is produced by the heat of compression and completeness of combustion may be influenced by the temperature distribution in the combustion chamber, it is not impossible that smaller cylinders may be more troublesome with regard to emissions than larger ones. Since the smaller engines are likely to find use in delivery vans and similar vehicles that are left to idle a lot, they deserve particular attention.

Diesels have one saving feature: their crankcase emissions are negligible. This is because they compress air only, and consequently the blowby gases consist of up to 85-90 percent air, whereas in premixed charge engines there is the same percentage of unburned fuel mixture.

Since significant numbers of diesels are now in use (not only on the highways) and their use is apt to increase to some extent, further research on diesel emissions is not only desirable but

imperative. Such information would also be applicable, at least in part, to those unconventional engine processes that do not operate with a premixed charge.

UNCONVENTIONAL ENGINE PROCESSES

Of all alternatives to the standard gasoline and diesel engine processes none owes its existence to a desire to solve the exhaust emission problem. Where claims in that direction are being made, they are the result of afterthought. The driving force behind the search for new engine processes has been the desire either to broaden the range of fuels that an engine can be operated on or to improve fuel consumption. These two aims are not always clearly apparent, and therefore we will not attempt to classify the engine processes accordingly.

It is more useful to postulate what requirements engine processes must satisfy if they are to be commercially interesting. It must be recognized that the engine and automobile industry is no longer a growth industry and that it is therefore highly competitive. Consequently, the industry will not make changes lightly. A clear competitive advantage must be realized by a change, since every change involves risk and capital outlays. An engine process that has other advantages while at the same time solving the emission problem could no doubt attract serious interest today.

Broader Fuel Base

Fuel properties, particularly knock rating, have never held back engine development to the extent at times anticipated. Fuel development has kept pace with the growing ability of engines to employ higher compression ratios. A certain plateau has been reached lately because of greater public concern with fuel costs and because of the arrival of a new problem: preignition. The latter is susceptible to the same solution as the knock problem: neither will occur if the residence time of the fuel in the combustion is drastically reduced.

Texaco Process

The now-classic example of a process that demonstrates this fact is the Texaco process. The engine compresses air only. Fuel begins to be injected into the cylinder just before top center and is ignited almost immediately. Fuel continues to be fed at al-almost exactly the rate at which it can burn or at which it is desired to have it burn. With this process there never exists the

possibility for preignition by hot deposits nor for autoignition due to heat and compression of a premixed charge.

The Texaco process represents an extreme. Other processes have been proposed that do not go quite so far. They attempt to suppress knock by making the last burning part of the charge either leaner or richer than the early burning part. These attempts are not technically important, and they are usually by-products of solutions to other problems.

Key Requirement for New Processes

The most important factor sparking proposals for new engine processes has been the desire to reduce fuel consumption. Many of these attempts have been misguided, either because the knock problem was overlooked or because the process resulted in lowered specific output of the engine. The key requirement for any new process is that it must allow an engine to deliver the same power that it would deliver if it were operated by the standard gasoline-engine process. This requirement may be stated more specifically: the engine must deliver the same top speed and the same brake mean effective pressure (BMEP) as its gasoline-engine counterpart. If this requirement is not met or closely approximated, the process is not very likely to result in an engine that is more attractive than a diesel, because diesel fuel consumption is not likely to be bettered by any other approach.

Lower Fuel Cost

As already indicated, most unconventional engine processes owe their conception to the search for reduced operating cost. This aim can be reached through lower fuel consumption or through the ability of the engine to operate on a less expensive fuel. Although the latter avenue will close in time, it may still give the necessary incentive for development and acceptance of a new engine type. Current market conditions make lower fuel consumption an effective incentive. This is fortunate from the standpoint of air pollution control, since lower total fuel consumption will certainly alleviate the problem created by exhaust emissions. Still more important is the fact that low specific fuel consumption almost always reflects more efficient combustion or better cycle efficiency. (Improvements from better mechanical efficiency do not reduce exhaust emissions.) Since it is not likely that the specific fuel consumptions of diesel engines can be bettered, it follows that any new engine process must incorporate other features in addition to low fuel consumption if it is to find acceptance in preference to the diesel.

Unthrottled Processes

The stated requirement that the specific output of gasoline engines must be obtainable with any new process means that full-load performance cannot differ very much from that of a spark-ignition engine. Therefore fuel consumption at full load will not differ greatly. Any improvement must come from improved part-load economy. Part-load specific fuel consumption can be improved significantly only by elimination of throttling for output regulation. This means that power must not be reduced by a proportionate reduction in both air and fuel flow (essentially constant fuel-air ratio) but by a reduction in fuel flow only (variable fuel-air ratio). Thus any new process will operate lean at part load. Two thermodynamic advantages result from this: the throttling loss is eliminated, and for a given load the ratio of the specific heats is greater, approaching that of pure air as the load is reduced. The greater this ratio is, the greater is the cycle efficiency.

The practical problem is to operate an engine at part load on mixtures that are leaner than those ever usable in a standard gasoline engine. The diesel solved this problem long ago, but since we argued earlier that the diesel is not the perfect answer, we must state what else we want. The requirement that the new process must give the same full-load output as a standard gasoline engine means that the new process must in effect be identical at full load with that of the gasoline engine. In other words, no matter how the process operates at part load, at full load it must use an essentially homogeneous charge. This in turn imposes currently the limitations that the fuel must be automotive gasoline and that ignition must be by electric spark.

Although at full load the emissions of the just-postulated engine do not differ fundamentally from those of a standard gasoline engine, there should be quite a difference at part load. The emission of unburnt and partially burnt hydrocarbons is not predictable and will depend on the characteristics of the process. The total production of oxides of nitrogen should be less because at the most important operating conditions the presence of considerable amounts of excess air reduces the combustion temperatures and thereby the extent of dissociation. If in addition a large portion of the cylinder charge is fairly lean, dissociation will even be less.

An important advantage of the postulated process is that no mixture control is required except at full load. This greatly reduces the changes for off-design operation and the resultant possibilities for excessive exhaust emissions. If all or part of the fuel is supplied with the air in premixed form, and even if this produces manifold wetting, acceleration enrichment will not be needed. On deceleration, some of the fuel will be picked up from

the manifold walls, but this will not cause an emission peak because this fuel will not be excess fuel as far as the combustion process is concerned. It will simply not let the power be cut as sharply as would be expected from the change in fuel flow. Similarly, a deceleration cutoff is not needed for the purpose of eliminating excessive exhaust emissions but, since cutoff is simpler to achieve than on a constant-mixture-ratio engine, it will probably be desirable to provide a deceleration cutoff to take advantage of the resulting fuel saving.

One more point is that in an unthrottled engine the cylinders do not pull any substantial vacuum, even on deceleration. Therefore, no lube oil will be sucked into the cylinders when power output is slight or zero. This eliminates spark-plug fouling and emissions due to incompletely burned lube oil.

The Ignition Problem

Lean mixtures cannot be ignited by the conventional electric spark. The lean limit in a standard gasoline engine is given by the leanest mixture that a spark can fire. This is not a clearcut point. Many variables affect the lean limit, but it can rarely be brought below an equivalence ratio of 0.85. Attempts to lower this value by changing the character of the spark or the design of the spark plug or by homogenizing the mixture produce only relatively limited gains when it is considered that at idling the equivalence ratio in an unthrottled engine is 0.2 to 0.25.

Yet a lean mixture can be ignited if enough energy is supplied to it during the ignition process. Thus we can either "amplify" the spark, or we can "stratify" the mixture so that all or most of it is concentrated in front of the spark plug in a patch that is rich enough to ignite readily, or we can spray fuel against the plug.

OTHER POSSIBILITIES

Among the other possibilities for engine modification, a very basic scheme is to cut out cylinders as the load is reduced. This can be accomplished by the application of a certain amount of gadgetry to a standard gasoline engine, but the process entails serious problems at the transition points and with engine balance.

Other schemes involve the change of engine displacement with load. This change can be effected by means that physically reduce the stroke. Or the effective intake stroke can be changed by manipulation of the intake valve timing, coupled with changes of the compression ratio by suitable devices. Still other ways of accomplishing essentially the same thing have been suggested or

can be deduced, especially if the possibilities of opposed two-cycle engines and compounding are considered. Most of these schemes have little interest until practical solutions for the resulting mechanical and other problems are offered.

Rotary Piston Engines

The questions might be asked whether rotary piston engines will permit new types of engine processes and whether they offer advantages regarding exhaust emissions. Such engines are in the news since the NSU-Wankel engine appeared. Since combustion in the NSU engine resembles in most important aspects that in reciprocating engines, the exhaust emissions should largely be the same. Certainly some kind of unthrottled process can be applied to the NSU engine, as can the diesel process, provided all mechanical problems inherent in such conversions can be solved.

It has been claimed that the low specific weight of the NSU power plant permits its operation at reduced peak power, that is, at leaner fuel-air ratios than that necessary for peak power. Such operation would reduce the emission of unburnt hydrocarbons and of carbon monoxide. In other respects, however, the engine would be neither significantly better nor worse than a standard gasoline engine as long as conventional carburetion is used.

Two-Cycle Engines

Two-cycle diesels are no different from four-cycle diesels with respect to exhaust emission. This is not the case with two-cycle gasoline engines. It has been shown in the laboratory and in the market place that injection can bring about considerable improvements in performance and fuel consumption, but currently no injection-type two-cycle vehicle engine is being marketed. With a carburetor, scavinging is of necessity by fuel-air mixture, and this obviously results in heavy emission of unburnt fuel through the exhaust. Since lubrication is by admixture of lube oil to the fuel, much partially burnt oil is exhausted. The well-known blue smoke from two-cycle engines is evidence of this, and its odor attests to the emission of great quantities of aldehydes. At light load and idle, misfiring because of poor scavenging is prevalent, adding further to the atmospheric pollution.

Since injection and other corrective measures add considerably to the cost and complication of an engine, the chief merit of which is low cost and simplicity, the gasoline two-cycle engine would be of interest only if it lent itself more readily to an unconventional engine process than four-cycle engines do. This possibility will be discussed later.

Available Information

In general, only very sketchy information is available on vehicle performance with the proposed and possible processes that have been discussed. What information is available is often of limited value because it has been obtained under idealized laboratory conditions. There are many pitfalls between the dynamometer and the car in the ultimate user's hands. Thus, any appraisal of the value and practicability of the various processes calls for a great deal of conjecture.

It has been mentioned that data on the exhaust emissions of unconventional processes are practically nonexistent. Since knowledge about the combustion process in standard gasoline and diesel engines is still fragmentary and new processes introduce new factors, the question of whether a new process will alleviate the air pollution situation is even more difficult to answer. Because of this, the following discussion of particular processes must sidestep many questions and answers.

NEW ENGINE PROCESSES

STRATIFIED-CHARGE ENGINES

If gasoline or any other fuel is to be used in a spark-ignition engine, the one inescapable requirement is that there must be an ignitable mixture at the spark plug at the time the spark occurs. If the engine is to operate with a premixed charge but without throttling at part load, that is, without a reduction of charge weight, the desired result can be obtained by dividing the charge into two zones, one containing air only, the other containing fuel and air in conventional proportion (equivalence ratio of about 0.85 to 1.3 or more). The spark plug must, of course, be located within the latter zone.

This would be true "stratification." Although it probably can never be fully attained in a high-speed engine, it will serve here as a common heading under which several engine processes can be discussed.

Two-Cycle Engines

In contrast to four-cycle engines, two-cycles engines operate with very little charge turbulence. This is so because designers of two-cycle engines have always attempted to achieve scavenging through displacement of the products of combustion of the preceding cycle by the fresh air or by a mixture that the scavenging pump forces into the cylinder. If there is turbulence and

undirected air flow, mixing will occur and this reduces scavenging efficiency. In four-cycle engines, gas velocities are higher and the air follows a tortuous path through the valves so that much more turbulence results.

Consequently, two-cycle engines should lend themselves better to stratification. Although little of practical value has reached the literature, an experiment reported by Voit and Stoll illustrates the potential of this system.[16] Into a loop-scavenged cylinder with a special head that has several spark plugs, a small quantity of fuel was injected. The resulting mixture patch was found to move in a very orderly manner through the cylinder, as evidenced by the fact that ignition occurred only if a particular plug was fired at a definite time. This experiment confirms the absence of factors that promote mixing. Unfortunately, if fuel distribution is entirely the task of the nozzle, it becomes very difficult to distribute the full-load quantity of fuel evenly.

In the same article the authors describe another approach. They put a suitably shaped cavity into the piston and sprayed into it. Most of the fuel would remain in this cavity and would be carried to the vicinity of the spark plug as the piston rose. After ignition, the further rise of the piston would produce squish (compression turbulence), thereby mixing all the air with all the fuel. No more than exploratory experiments were made.

Four-Cycle Engine with Intake Introduction of the Fuel

The French automobile firm of Citroen has apparently devoted much effort to the problem of lean-mixture operation. Nothing more is known about this effort except what the firm found worthwhile to have patented. Of interest here is a patent that concerns stratification in a four-cycle engine in which fuel is injected through the intake valve when it is open (see Figure 1).[17] The patent concerns itself principally with the reduction of turbulence during the intake stroke. Obviously, if this endeavor is successful, the problem of producing the desired fuel distribution at full load is less severe than in a two-cycle engine because much more time is available. Injection duration and timing can be varied over a wide range. The patent gives no clue to how successful the approach is, and information from other sources is not available.

The patent does indicate that the compression turbulence is used to promote mixing after ignition. It also reveals that perfect stratification is not obtained.

A somewhat similar approach was taken some 20 years ago by Boghetto,[18] according to whose ideas Fiat in Italy built an

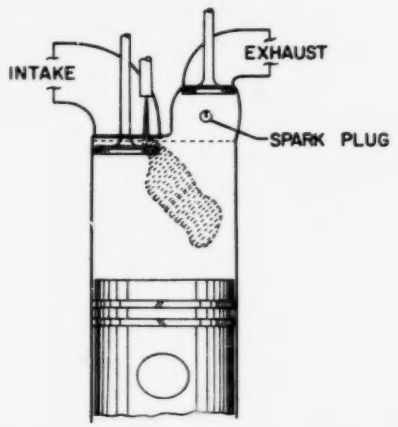

Figure 1. Citroen stratified charge engine.

engine. Quite similar was a system proposed later by Starr in the United States.[19] The entire compression volume of these engines was located in a cylindrical or conical chamber in the head. At the apex of this chamber was the nozzle, and the spark plug was situated slightly below in the chamber wall (see Figure 2). Hot residual gases collected in front of the nozzle during the compression stroke. When injection occurred, just prior to ignition, fuel evaporation was speeded by these hot gases. This apparently insured very low penetration with small fuel quantities and therefore an ignitable mixture at the plug. However, below

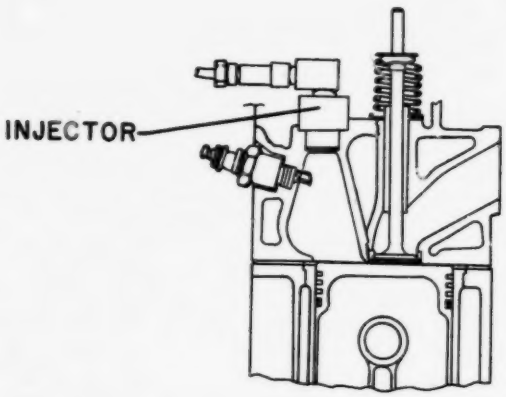

Figure 2. The Starr engine.

quarter-load, half the cylinders were cut out on the Starr engine to insure proper running. Maximum BMEP and specific fuel consumption were not very interesting, even though the engine had considerable squish.

Stratification by Swirl

One method of obtaining fairly orderly air motion in an engine cylinder is by so bringing the air in that the cylinder charge rotates. In some two-cycle types, rotation is used to assist the scavenging process, but because of this the rotation cannot be designed to suit the mixture formation process. In four-cycle engines this restriction does not apply. Ordering the air motion in this manner during the intake process reduces the turbulence during compression.

The earliest attempt to employ "swirl," as this air rotation is commonly called, is found in the Hesselman engine, which appeared on the market in the early 30's as a "low pressure diesel." It was built in this country until after World War II by Waukesha Motors. Its concept circumvented many of the problems that plagued early high-speed diesels, and this accounted for its commercial success. Descriptions of it can be found in nearly all textbooks on internal combustion engines. More details can be found in the Swedish and German technical literature.(20)

Air rotation was produced by a "shrouded" intake valve; that is, the valve had a shield on its back side that permitted air to pass into the cylinder past only part of the valve circumference. (Today the same effect would be obtained by a suitably faired approach of the intake duct to the valve. The valve is then free to rotate, and also the loss in volumetric efficiency is reduced.)

A nozzle injected fuel into the air during the compression stroke as the air moved past the nozzle. The spray reached from the cylinder periphery approximately to the center. The injection rate was such that, for instance at half load, half of the air charge was impregnated with fuel. Injection ended always at the same point of the cycle, irrespective of load, just prior to spark occurrence. The spark plug sat diametrically opposite the nozzle at the combustion chamber periphery (See Figure 3.)

Although the engine was intended for diesel fuel, the compression ratio was low (about 8:1) because detonation would occur. This was in part due to the almost complete absence of mixing after ignition. No squish was used. To insure steady idling, some throttling was necessary. In later models, half the cylinders were cut out. The fuel consumption was not good, but in the engine's heyday diesel fuel was cheap. On diesel fuel, the

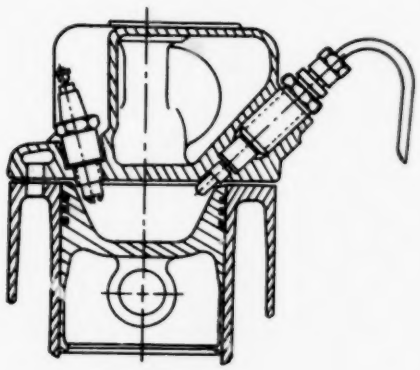

Figure 3. The Hesselman engine.

engine had about the same smoke limit as a standard diesel. Gasoline could be burned in this engine, but there was little incentive to do so at the time.

Although everything points to poor exhaust performance of this engine and to its unsuitability for passenger-car use, it would be interesting to redesign it in the light of present-day knowledge. There are more modern processes that at least superficially appear to be descendents of the Hesselman.

One of these is the process proposed by Witzky and explored by The Pennsylvania State University.(21) Air swirl is used; the nozzle sits near the periphery of the cylindrical combustion chamber; the spark plug is near the center; the piston has a concentric, flat, cylindrical recess; and there is some squish (see Figure 4). Witzky's original idea was that, by spraying across the air swirl, secondary flow in the swirl would concentrate a large portion of the fuel in the center. Bomb tests showed that this is not the case, but it was found that the desired effect can be obtained by proper coordination of spray and swirl.

Unthrottled operation down to 60:1 air-fuel ratio (0.25 equivalence ratio) was possible. Since only little experimental work could be carried out, the not particularly good fuel consumption and the low maximum output are not considered final values. Best results are obtained if injection is late (less than 80° BTC) at high load. From experimental evidence it was concluded that this made the charge at high load very nearly homogeneous, while at light load it was reasonably well stratified. As measures for improving the performance, increased squish or a second spark plug

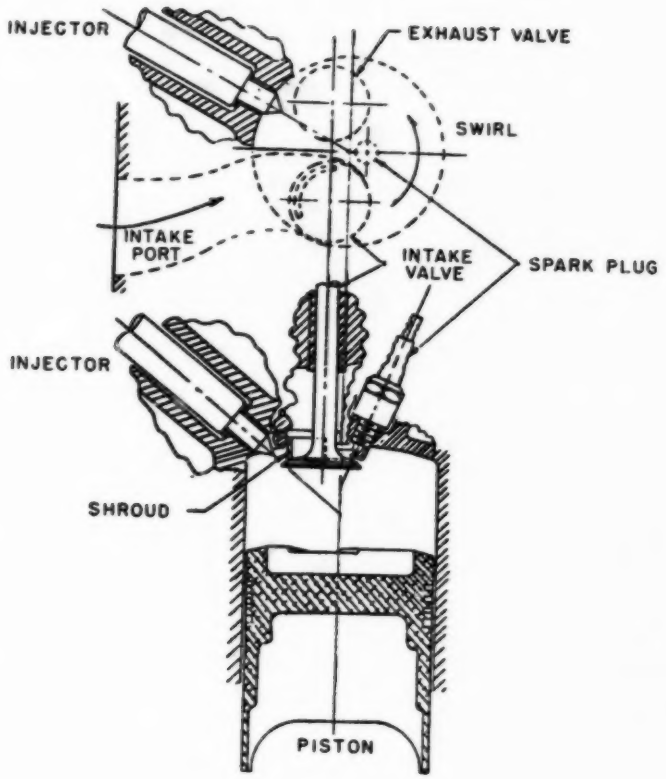

Figure 4. Witzky experimental engine.

at the chamber periphery are suggested to combat suspected slow burning.

No analysis for exhaust emissions was made except a test for carbon monoxide at idle. None could be found by Orsat analysis. If slow burning was indeed the cause for the less-than-expected performance, chances are that the exhaust contained unburnt hydrocarbons. (All tests were with gasoline as the fuel, but JP-4 could be burned with equal results. No detonation was experienced with the 10:1 compression ratio.)

Summary

Despite the soundness of the stratification concept, no one has yet been able to produce stratification sufficiently well to

prove that with it a wholly satisfactory engine can be produced. It does not seem, however, that this is impossible.

Such an engine would have full-load exhaust emissions not much different from those of a standard gasoline engine. At part load it should be considerably better, not only in the concentration of the undesirable constituents in the exhaust gas flow, but in their total quantity. The degree of improvement will depend on the internal structure of the fuel bearing zone.

ENGINES WITH ENRICHMENT AT THE SPARK PLUG

If full stratification is difficult to achieve, one might seek a solution via a less ambitious path, by limiting stratification to a small patch in front of the spark plug. The mixture surrounding this patch can then be quite lean because even very lean mixtures will burn once reaction has been initiated. This basic idea has been applied to many proposed engine processes. Because of their inherent similarity, each will be dealt with only briefly.

Ignition Cells

The easiest way to insure that the spark will find a mixture that it can ignite is to place the plug into an auxiliary chamber to which fuel is supplied in the required amount. The main chamber contains the rest of the fuel in homogeneous mixture with the air at the ratio dictated by the desired engine output. Upon ignition by the spark, a hot jet of gases issues from the auxiliary chamber and ignites the mixture in the main chamber. The jet produces mixing and turbulence, thereby speeding the otherwise slow combustion of a lean main charge. Squish can be used to further accelerate burning.

If at very light loads burning velocities are still too low to give good cycle efficiency, throttling can be resorted to. Such throttling introduces no serious losses since the mixture is still quite lean and throttling is slight. Furthermore, because the fuel-air ratios are not critical, no complicated mixture control device is needed, nor does wear in the throttle mechanism affect engine performance.

Dodson and Lentz made exploratory tests at The Pennsylvania State University with a simple ignition cell on an aircraft cylinder.(22) In place of the spark plug, an air-cooled cell was inserted that contained about 20 percent of the compression volume of the engine. The spark plug and an injection nozzle were mounted in the cell. Twenty percent of the full-load fuel quantity was injected intermittently into the cell, and the main chamber

was supplied with variable amounts of fuel from a nozzle in the intake pipe.

The engine idled, without throttling, on the cell fuel alone. Part-load consumption was better than with the normal process, but maximum output was less. Two things were noteworthy: reasonably good performance was obtained on first try, and there was smooth transition from operation on cell fuel alone to operation with main fuel added. These experiments were continued at the Packard Division of Studebaker-Packard Corp., but soon terminated because of the cessation of all activities at Packard.

In Russia a similar approach was taken by Nilov,(23) except that the cell is fed with a stoichiometric or richer mixture produced by an auxiliary carburetor, via a valve that is slaved to the rocker of the main intake valve (see Figure 5). This engine apparently has been developed to a high state of perfection and seems to be ready to go into production. Nilov gives a graph that shows that maximum output is about 10 percent less and minimum specific fuel consumption about 20 percent less than with an equivalent standard carburetor engine.

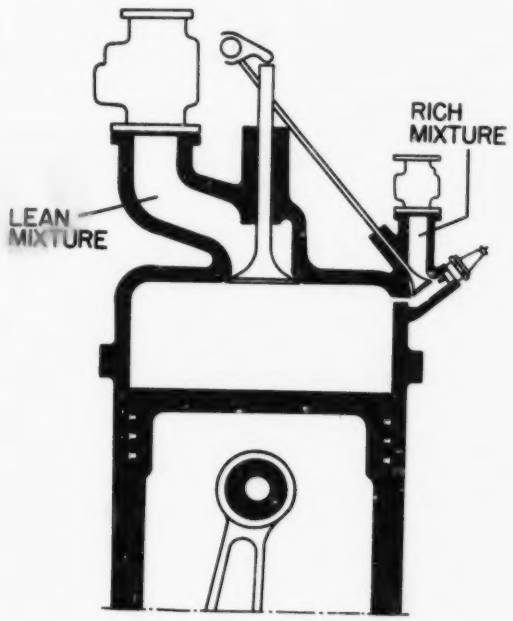

Figure 5. The Russion "Jet Ignition" process. This illustrates the version employing a premixed main charge.

There is a fairly long recent paper (1960) on research on this combustion process by Sokolik and Karpov.(24) Of interest here is the conclusion that throttling at very light loads will improve fuel consumption. Low octane requirements are claimed, and the statement is made, but not substantiated, that the engine will solve the air pollution problem "because of the elimination of products of incomplete combustion, and in particular of carbon monoxide."

In this country, Heintz has independently followed a similar path.(25) Heintz uses a somewhat more complex prechamber, but this is the only major feature that differs from the Russian design. The published performance data are similar. Throttling is used to keep the minimum air-fuel ratio below 30:1; "otherwise a very low combustion temperature results and combustion is quenched before the fuel is completely burned." With throttling "incomplete combustion is reduced to 2 percent (both carbon monoxide and hydrocarbon) of the supplied fuel quantity."

Heintz has since modified his process and applied the new version to both two-cycle and four-cycle engines that he intends to install into automobiles. No data are available on these engines as yet, nor is any information on the process they employ.

Recessed Spark Plugs

The ignition cells discussed so far all have relatively narrow exits. Sokolik and Karpov argue that the hot jet emerging from the cell must have considerable velocity because the turbulence produced by it is essential to the attainment of sufficiently rapid combustion. Whether this is correct is not known at this point.

It is conceivable that judicious use of squish and throttling beginning at a somewhat higher fuel-air ratio may very well be made to compensate for (though not replace) a reduction in ignition-cell-induced turbulence. If this is so, the cell might be converted into a plain cavity. This has the advantage of reducing the flow losses at the exit and eliminating a hot spot that may cause preignition. (Evidence of preignition has been observed in the Heintz engine and at Packard.) With the restriction removed, the injection nozzle in the cell may then also be used to inject the needed fuel into the main chamber. This approach was taken by Ricardo on a two-cycle engine.(26)

In Ricardo's plan the recess was in the head, concentric with the cylinder axis. The nozzle sprayed from the recess along the axis into the cylinder during the early part of the compression stroke. Just before the plug fired (it was also located in the

recess) a second injection (at lower pressure to reduce its penetration) occurred that enriched the mixture in the recess (see Figure 6). The engine idled without throttling and appeared otherwise promising, but difficulties with the injection system led to abandonment of the project.

No further work along the lines of Ricardo's idea has become known, but the Broderson method [27] might be considered an extension of it. Here the nozzle is placed at the juncture between the cavity and the main chamber. A single injection period is used, but (on a four-cycle engine) it can be so timed that either the gas flow from the cavity into the cylinder during the intake stroke carries the fuel into the cylinder or the reversal of the flow during compression carries it into the cavity (where the plug is located) (see Figure 7). In practice, the injection occurs around bottom center, and by proper timing the desired proportions of fuel are directed into cylinder and cavity. Promising laboratory results have been obtained, but demonstration of the process on a realistic engine is still to be made.

Schlamann in Holland has given the cavity the shape of a turbulence chamber.[28] He injected part of the fuel into it and the rest was introduced with the intake air. There was no throttling. Early results were called "promising," but nothing further was heard about the design.

Enrichment Near the Spark Plug

Instead of holding a rich patch near the spark plug by recessing it, one can attempt to solve the problem by leaving the

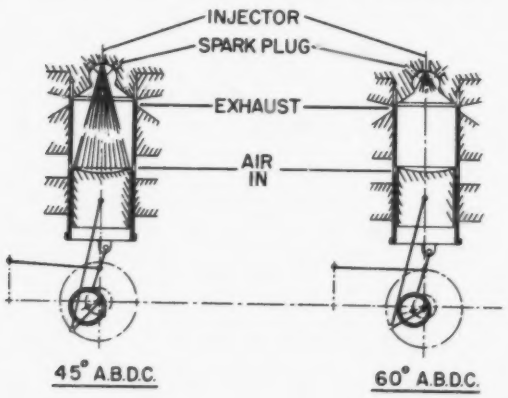

Figure 6. Ricardo unthrottled sleeve-valve two-cycle engine

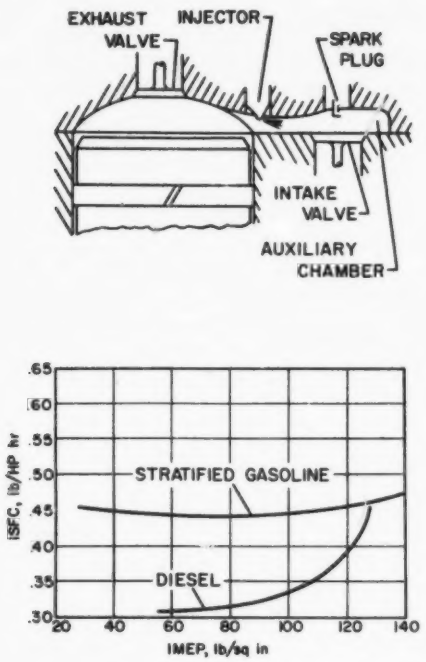

Figure 7. The Broderson process

plug in the wall of the regular combustion chamber and spraying at the plug or its vicinity immediately before the spark occurs. This secondary injection may have to be larger than with a cavity to insure ignition under all conditions.

F. A. F. Schmidt of Germany has demonstrated that this can be done, although the data he gives are sketchy.(29) He apparently used an aircraft engine with cylinder injection and simply injected the fuel in two stages of (apparently) equal quantity. The first injection took place during the intake stroke, the second "very late." He states that "the engine can be operated successfully at much lower fuel-air ratios than with normal injection." Actually his main gain seems to have been a 25 percent increase in knock-limited power. (Heterogeneous charges are usually more knock-resistant than homogeneous ones.)

A similar but more rigorous approach has been suggested.(30) Here nozzle and plug were to be arranged at diametrically opposite locations of the combustion chamber. The first injection was to be intercepted by the incoming air, that is, it was to take

place during the middle of the intake stroke. The second injection (from the same nozzle) was to be very small and essentially independent of load. It was to occur just before the plug fired. At that time no significant deflection of the spray was expected to occur, so that a rich patch would form at the plug. This suggestion was never tried out.

Baudry of the Institut Francais du Petrole (IFP) has attempted to attain these objectives with a carburetor.(31) Since he adds very little complication and cost to the engine, he has succeeded quite well, even though he must throttle at equivalence ratios below 0.5. He brings a small tube which carries a very rich mixture, as close to the intake valve as possible and bends its end to one side (see Figure 8). The main air carries a variable amount of fuel (see Figure 9). The part-load fuel consumption is good, and maximum output is the same as that of the original engine (see Figure 10).

Why the Baudry system (IFP process) works is not quite clear. The directed rich mixture introduces some swirl into the dome-shaped combustion chamber. The plug has to be located near the tube exit and directly downstream from it. With other plug locations, the lean limit is higher. Since the fuel is introduced entirely during the intake stroke, the rich patch must survive the entire compression stroke. Why this patch should then end up at one plug location only, irrespective of engine speed and

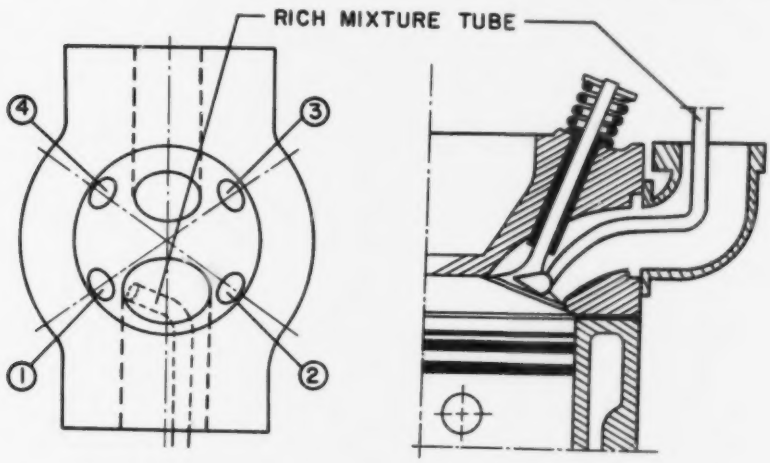

Figure 8. IFP process as used in experimental single-cylinder engines. Numerals refer to spark plug positions. No. 1 position proved to be superior to all others.

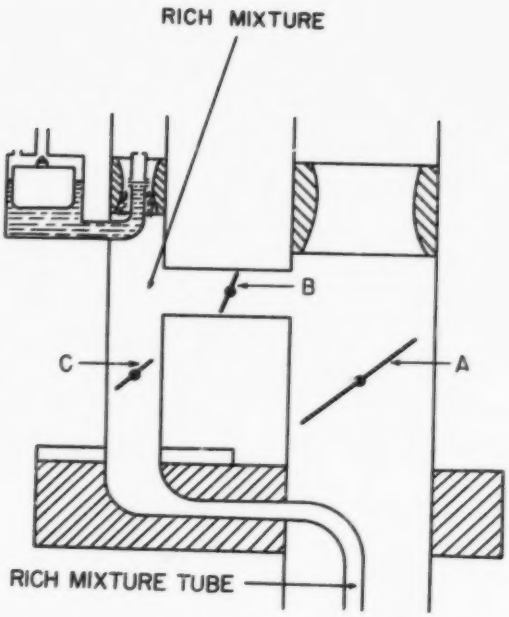

Figure 9. Proposed fueling system for IFP process engine. Valve A remains wide open at equivalence ratios above 0.5; B and C control the proportion of fuel in main inlet and rich mixture tube.

spark timing, has not been explained. It may be that some fuel "hangs up" in the plug cavity itself and this would favor the plug location closest to the rich mixture tube.

Baudry gives data only on carbon monoxide emission, which is in line with what one would expect: normal at full load and decreasing to negligible concentrations at part load.

Summary

Baudry's results may be taken as proof that an unthrottled process can be created that is acceptable from an economy and performance standpoint. Whether an engine incorporating his process would fully satisfy in a vehicle remains to be seen. In any case, better knowledge of how the Baudry process functions may open the way to a more sophisticated and wholly satisfactory solution.

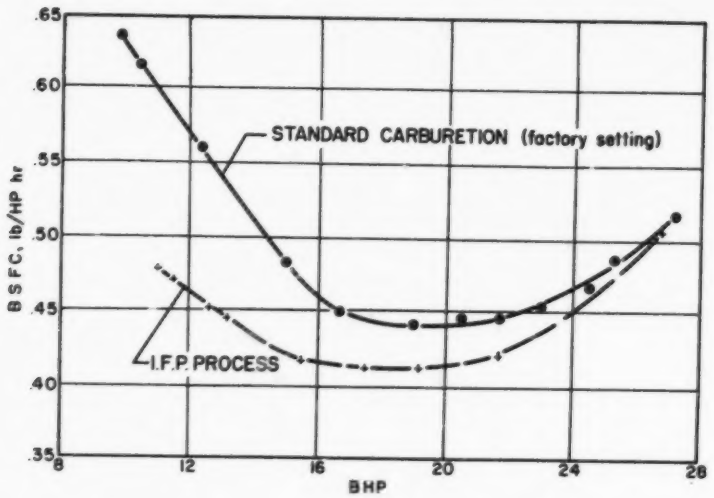

Figure 10. Improvement in part-load fuel consumption of a small automotive engine (Dyna-Panhard, 2 cylinder, aircooled) after conversion to IFP process

What has been said about emissions under the heading of stratification applies here also, except that at light loads slow combustion may introduce difficulties. But these can probably be avoided by throttling. Unfortunately no documentation is available as yet on exhaust emissions from very lean homogeneous mixtures. Wall quenching may well be a problem, particularly if squish must be employed either for knock control or for speeding up the burning of the last portion of the charge. (Stratified engines should be superior in this respect, particularly if the residence time of the fuel in the combustion chamber is short and more so if the fuel can be so injected, at least at part load, that wall contact is essentially prevented.) Clarification of this point is a matter of some urgency. If an investigation shows that such mixtures do not burn acceptably, a lot of misdirected effort would be prevented.

There remains the question of the emissions during acceleration and deceleration. A variable fuel-air ratio engine with enrichment at the plug will respond well to the throttle (even if a "carburetor" is used) because there is no danger of lean misfiring. However, emissions may still increase during acceleration because combustion chamber wall temperatures may be temporarily too low for complete combustion of a suddenly enriched mixture. Further studies are needed in this area. A

fairly well developed engine is necessary to evaluate the processes discussed above. None is yet available, with the possible exception of the Baudry engine.

ENGINES WITH INJECTION ON THE COMPRESSION STROKE

The diesel process has the merit of low part-load fuel consumption and freedom from detonation knock.

A diesel must have a very high compression ratio if a fuel of poor ignitability is to be burned. Extremely high compression ratios are undesirable, and therefore many attempts have been made to promote autoignition by other means. Of practical interest here are only those processes involving spark ignition. If this could be done, ignition could be produced at any compression ratio, and ignition delay would always be positively controlled. Part-load economy would still be good compared with that of gasoline engines. Since no detonation-knock limit exists, gasoline can be used and it does not have to have any specific octane rating.

Spark Ignition

Simple insertion of a spark plug into a regular diesel combustion chamber has never been successful because it is impossible to keep the plug from either being drenched or receiving too little fuel at one or more points of the speed and load spectrum. However, if orderly air motion is employed, this difficulty can be overcome.

This is the approach taken by the Texaco process.[32] In a four-cycle engine, swirl is produced by a shrouded intake valve or swirl port. Fuel is injected tangentially into the swirl; shortly after, or as soon as, the spray reaches the spark plug (located a short distance downstream from the nozzle) it is ignited by the spark. The subsequent burning rate is controlled by the rate of injection. (The latter must be related to the swirl rate if all the air is to be utilized.)

This process is free of diesel and detonation knock; in fact, it owes its origin to the search for a process that would not be knock-limited. It has gone through many years of development, and, by the addition of squish, air utilization nearly up to stoichiometric has been achieved. For a selected compression ratio, the possible maximum specific output is therefore higher than with a diesel but lower than with a gasoline engine operating on an overrich mixture. Fuel consumption compares favorably with that of the diesel at all part-load conditions. All gasolines, as well as jet and diesel fuels, can be used.

Texaco engines have a smoke limit, as do diesels. Near this limit, exhaust emissions are similar to those of diesels. The Texaco and the diesel processes differ, however, and therefore the part-load emissions are not necessarily similar. Data furnished privately by Texaco on an older engine model indicate 15 to 75 ppm unburnt hydrocarbons (as hexane) at part load. Oxides of nitrogen increase from about 100 ppm at 20 percent load to somewhat above 1000 ppm at full load. Carbon monoxide emission is practically zero up to 80 percent load. Texaco concludes that current California regulations can be met comfortably and that emission of oxides of nitrogen is considerably lower than that of gasoline engines except possibly during full-throttle acceleration.

Ignition Cells

As already stated, the mere insertion of a spark plug into a diesel engine does not produce a usable engine, but if an ignition cell is used instead, very interesting results are obtained.

Birnie and Meyer report exploratory tests on such a process.[33] A very small cell (5 percent of the total combustion chamber volume) containing a spark plug received fuel through a nozzle just prior to spark occurrence. The normal (main) injection from a six-hole nozzle was so timed that the spray arrived at the ignition cell at the same moment at which the hot gas jet issued from the cell. With gasoline the engine operated satisfactorily and without diesel knock in dynamometer tests.

A similar approach is described by Sokolik and Karpov in their already mentioned paper on "jet ignition."[24] They give little data, but state that gasolines of octane numbers from 20 to 70 will give identical power and economy without knock and that 95 to 100 percent air utilization is possible without smoke, but that throttling at light loads is desirable. The fuel was apparently introduced into the cell as a premixed charge. Nothing indicates at what time in the cycle the introduction took place.

The ignition cell undoubtedly provides some turbulence in the early stages of the combustion, and this insures more rapid inflammation of the fuel in the main spray than would be possible by direct spark ignition. In contrast to engines in which the main fuel is introduced through the intake as a homogeneous charge, no preignition problems exist because preignition of the main spray would be submerged in the jet ignition. Preignition of the cell charge, if it occurs, can probably be controlled by proper timing of the injection of the precharge so that preignition and spark ignition merge.

If the Russian claim that stoichiometric mixtures can be used is correct, this engine process may well be of serious

interest. It should be applicable to gasoline engine structures, since the "external" ignition permits lower-than-diesel compression ratios to be used. No information is available on exhaust emissions, but these should be very similar to those of diesels.

Summary

There can be little doubt that the Texaco process is important from the standpoint of tolerable exhaust emissions. The ignition cell process probably occupies a similar position. The question, therefore, is whether any of these processes will find acceptance. Such engines will be more expensive than gasoline engines because they require high-grade injection systems that cannot be cheap. They also have lower output for a given engine weight, but the specific fuel consumption approaches that of diesels. Combustion is smoother than in diesels, and there is no knock limit as with standard gasoline engines. The ability of Texaco engines to operate on either diesel fuel or gasoline has been much deprecated, but this may well provide the key to the acceptance of these engine processes. The ability to use whatever fuel is available at lowest cost, in conjunction with the elimination of the need for an afterburner, may well be sufficient to compensate for the higher first cost and the lower specific output.

OTHER POSSIBILITIES

It has been suggested that if a standard gasoline engine were to be fed with a better prepared mixture than a carburetor can furnish, exhaust emissions would be reduced. No data are available on this except that Huber has shown that carbon monoxide output is slightly greater if the engine receives a fully vaporized and homogenized mixture.[10] He concludes that this may be because some of the fuel, when supplied by a carburetor, does not participate in the combustion process; that is, the non-participating fuel does not produce carbon monoxide. If this is correct, the emission of unburnt hydrocarbons should be less with the "perfect" mixture.

Huber elsewhere[34] describes an engine process that incidentally produces a much better homogenized mixture than exists in a conventional engine. He calls this the "extended expansion" process because by closing the intake valve early he makes the expansion ratio greater than the effective compression ratio. This gives certain thermodynamic advantages that result in lower fuel consumption, but specific output is correspondingly decreased except at very low speed. The decreased output must be rated as a disadvantage, although Huber thinks differently. The engine has, with speed, a sharply declining torque curve, and

Huber feels that this so much simplifies the transmission problem that a somewhat larger engine would be acceptable.

If the intake valve closes while the piston is still descending, the cylinder charge will be expanded to pressures below atmospheric. This produces better mixing and evaporation, which Huber believes account in part for the better economy, if only because cycle-to-cycle irregularities are reduced. Emission of unburnt hydrocarbons may be reduced, but in the absence of measurements one cannot say by how much.

If an acceptable mechanism for changing valve timing were available, the main objection to Huber's process, namely the reduced output at full load, would be removed. If compression ratio could also be made variable, output regulation without manifold throttling would be possible, and substantial gains in fuel consumption and reduced exhaust emissions might be achieved. The necessary mechanisms have been proposed, but is is questionable whether they could be incorporated in an engine at acceptable cost.

NEW TYPES OF POWER PLANTS

Although the intent of this report is to discuss only the modifications that might be applied to existing engines, that is, internal combustion engines, it seems appropriate to say a few words about other types of power plants.

Gas Turbines

The gas turbine has recently received a great deal of publicity as the future power plant for automobiles. There is no doubt that the turbine will find application for a number of purposes where its advantages are clearcut. This includes fire engines and other emergency vehicles. For pulling one or several heavy trailers over turnpikes and interstate highways, turbines are unquestionably superior power plants. For other specialized applications also, the light weight, the torque characteristics, ease of starting, etc., will make the turbine a better choice than a piston engine.

In passenger cars and trucks for local or short-distance hauling, the turbine has not been considered competitive with existing engines, principally because of its high fuel consumption at light loads and idle. Regeneration and other measures have improved turbine part-load fuel economy considerably. Although on cross-country trips reasonably good mileage has been demon-

strated, no figures are available for city and suburban traffic operation. What information is available indicates that fuel consumption under these conditions is still prohibitively high.

Other characteristics of even the most refined gas turbines makes it questionable that they will soon be ready for use as general-vehicle power plants. Their bulk, for comparable performance, is no less than, and possibly greater than, that of piston engines (although the weight is unquestionably less); low-speed acceleration is poorer; and retarding with power off is less (unless reverse power is applied).

The greatest unknown is first cost. Only estimates exist. It has been claimed that turbine cost could be brought in line with that of piston engines if the production quantities were the same. It is difficult to say whether it will be possible to introduce the turbine gradually as a high-cost option or whether it will be necessary for a company to decide that a complete conversion to turbines is the best way. In the latter case the risk would be staggering.

The majority opinion is that the time will not be ripe for widespread introduction of gas turbines for several years to come. If that time does come, what will be the effect on air pollution? All available information indicates that the total emissions of hydrocarbons and carbon monoxide from the gas turbine should be very low and safely below currently permitted limits (see for instance the study by London(35)). It is not known whether this is true for all turbine types under all conditions and with all fuels that are likely to be used.

Electric Vehicles

There are no emissions from battery-powered, electrically driven cars. Current battery technology makes such cars possible and practical for trips of limited length. Their power-to-weight ratio, and therefore their performance, is largely a question of the action radius such vehicles are designed for. If intermittent recharging is made possible by charging stations at points at which the travel can be interrupted for sufficiently long periods, electric vehicles would be quite practical, although for most uses their first cost would remain high.

It is not impossible that electric cars and delivery trucks will find favor for special purposes. It does not appear that their number will become such that in large metropolitan areas, which are those with air pollution problems, the total vehicle emissions will be influenced significantly unless legislation (and subsidized development of a network of charging stations) forces their introduction.

Blue-Sky Solutions

Fuel cells, thermoelectric generators, thermionic generators, solar cells, hot-air engines, closed-cycle gas turbines, steam engines, and others have been proposed or reproposed as future vehicle power plants, in some case with utter disregard to fundamental and practical limitations. Most of these solutions will not be ready in the near future for anything except very specialized applications. It is extremely doubtful that any will ever become practical for road vehicle propulsion.

The writer can do no better than to quote from a excellent, recent comparative study of all possible power plants by Lauck, Uyehara, and Myers(36): "The new generators have many unique characteristics that will enable them to meet specialized needs, but it appears that the great majority of our everyday conventional-use producers of power will continue to be the old standbys, the steam power plant and the internal combustion engine."

CONCLUSIONS AND RECOMMENDATIONS

1. Total exhaust emissions from existing engines can be reduced by use of smaller engines, by novel types of transmissions, by storage of the kinetic energy that can be recovered during deceleration, and by engine shutdown during deceleration and vehicle standstill. With the known emission spectra of applicable engines, the reduction in emissions can be estimated if driving patterns, transmission characteristics, etc. are assumed. Only very rough estimating procedures are justified because of too many imponderabilia concerning performance of assumed components, their probable cost, industry and user acceptance, etc.

2. There are several new engine processes that promise an improvement of the exhaust emission spectrum. Unfortunately, none of them, with the exception of the Texaco process, has been developed far enough for meaningful exhaust evaluation. Until engines are in existence that demonstrate that a given process promises to be of practical value, emission studies will not be useful.

3. It may be practical to investigate whether basic features of certain processes do have a potential for reducing exhaust emissions. Such information would promote the development of more promising processes. Research of this sort would be useful only if carried out on a full-scale engine. The one area that lends itself to study without the need of developing a special test engine is that of lean-mixture burning. Such mixtures can be ignited by an ignition cell, which can be attached to almost any engine.

4. One might also fairly readily study the Baudry process, since it involves only simple changes that are external to the engine. The Baudry process is under development at the French Institute of Petroleum, and it is hoped that the Institute will carry out the necessary measurements of exhaust emissions and publish them.

5. Better homogenized mixtures in a conventional engine should also be studied. Such mixtures could be produced externally by a special "carburetor" and internally by early intake valve closing. On the test bed, changes in valve timing can be effected by means chosen for their simplicity rather than for practicability in a vehicle.

6. Diesel exhaust studies should be continued to get a clearer picture of what factors influence diesel emissions. More information is needed also on the mechanisms in which certain constituents, such as 3,4 benzpyrene, are involved after emission.

7. The potential of fuel injection in conjunction with a standard gasoline engine deserves further study. Since the performance of an injection system is principally a function of its mixture control device, and since such a system would involve intensive development, such a study can be made only after a system that is acceptable to a car maker has been released. No injection system that is intended only for use on sports cars needs to be studied because it would not give representative information.

8. Recent research has shown that wall quenching is the major source of hydrocarbon emission in conventional gasoline engines. It would be extremely valuable to determine the effects of combustion chamber configuration, turbulence, scavenging, and other variables on wall quenching as well as on the carryover of the unburnt mixture into the next cycle.

9. Efforts should be stepped up in the area of finding means for the reduction of the emissions during closed-throttle deceleration of conventional gasoline engines.

10. The emissions from an automotive gas turbine should be determined. At the same time, attention should be given to the various fuels that might be used in the turbine and to off-design operation (starting, worn injectors, etc.).

11. More information is needed on the distribution of emissions and emission-related materials in the atmosphere of cities outside of California. We need to know more about the driving patterns in such cities and the relative contributions to air pollution by various classes of vehicles, including trucks and buses. Special locations, such as taxi stands and bus stops should be

surveyed. Since in Eastern cities the worst air pollution situations occur in winter, surveys should emphasize the cold season. Such information is needed to better gage the seriousness of the emissions of engines operating in areas other than California.

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